The Higgs Boson: Theoretical Issues

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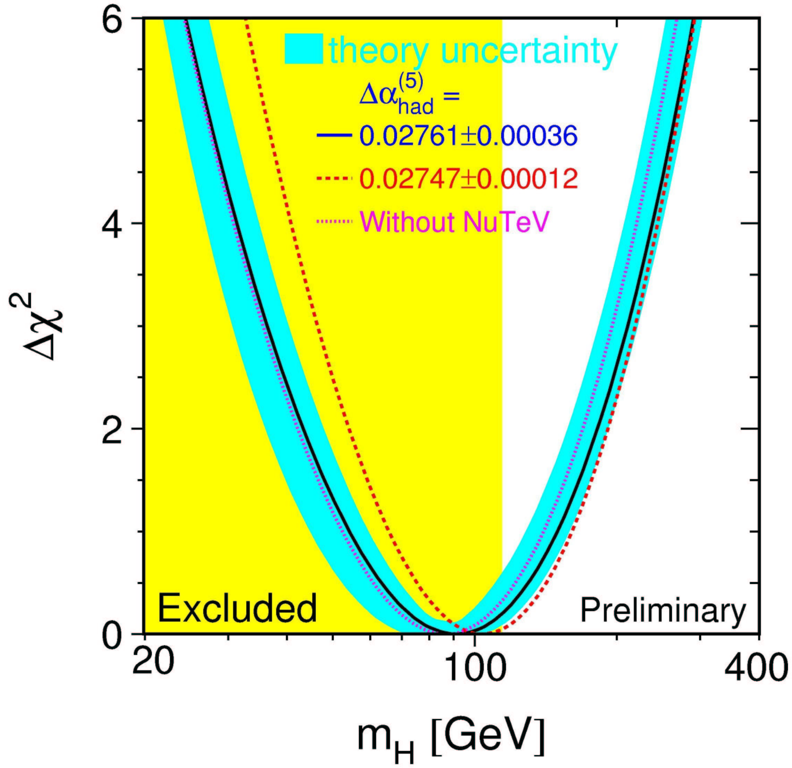
Aspen Winter Conference

February, 2004

- Thanks to my collaborators:

  C. Jackson, L. Orr, L. Reina, D. Wackeroth

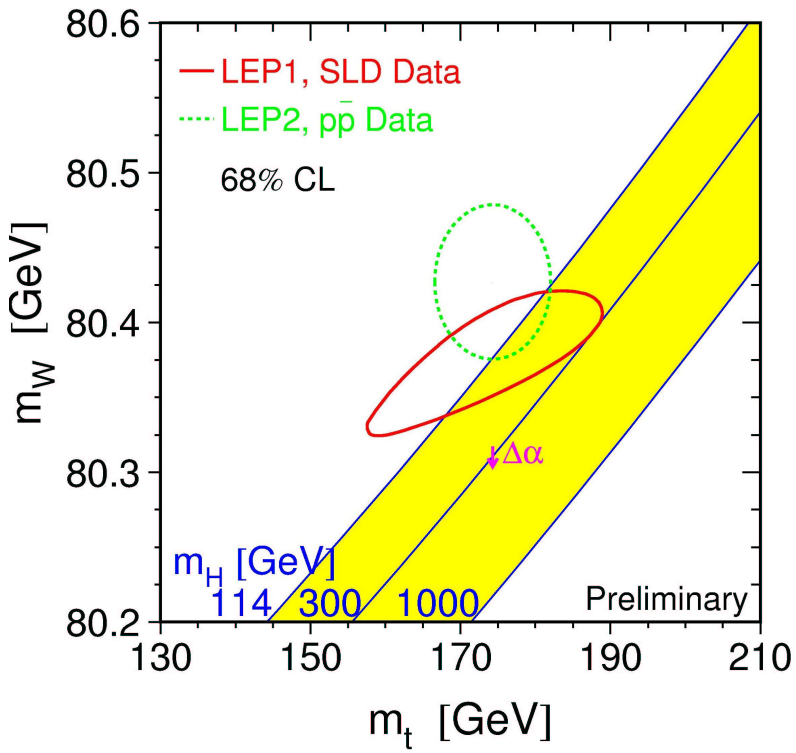
Precision EW measurements and the Higgs Boson



➢Removing nuTeV has little effect on fit

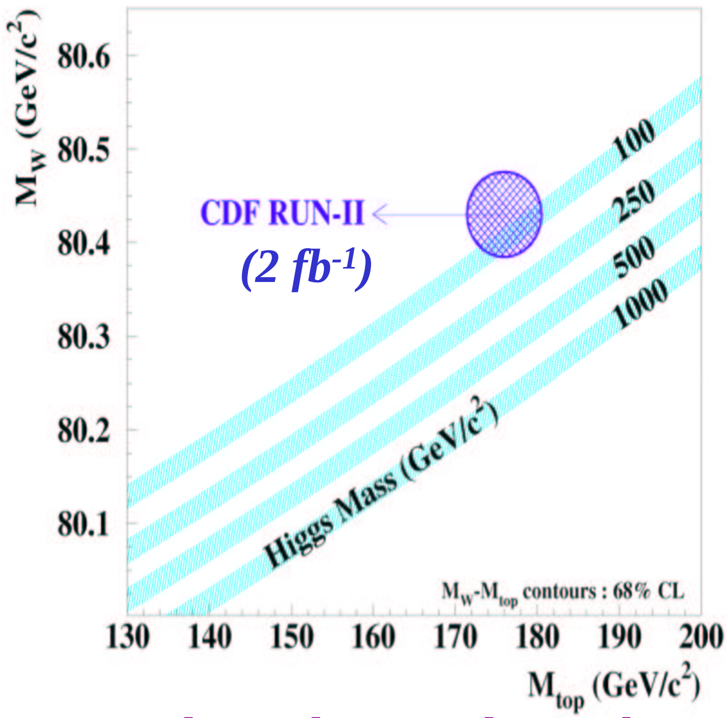
➢Note: Poor quality of fit

$M_h < 219$ GeV



Best fit: $M_h = 96^{+60}_{-38}$ GeV

Top Mass has drastic Implications for M_h



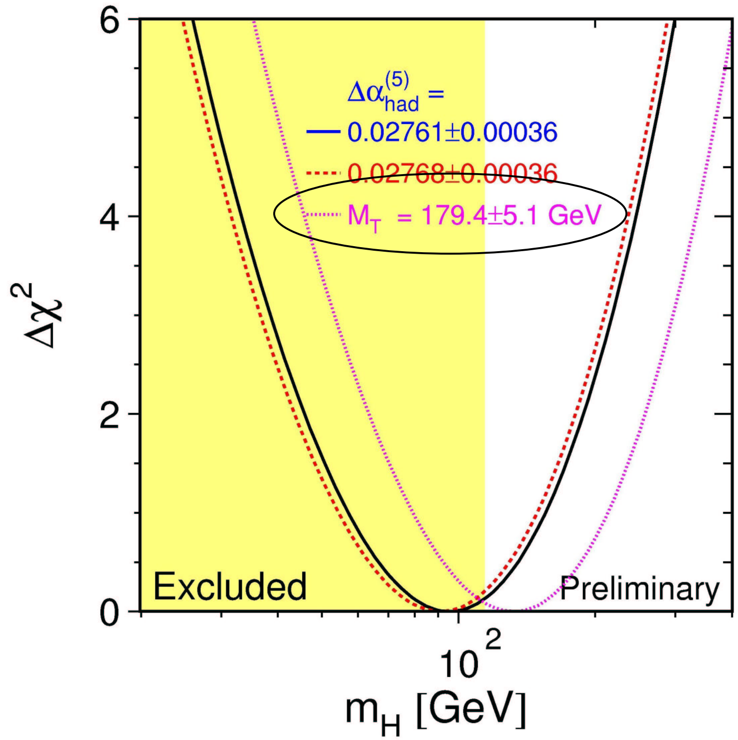
M_h dependence is logarithmic

M_t dependence is quadratic

Increasing M_t by 5 GeV increases M_h limit by 35 GeV

R. Claire, WIN03

Suppose M_t=179.4±5.1 GeV

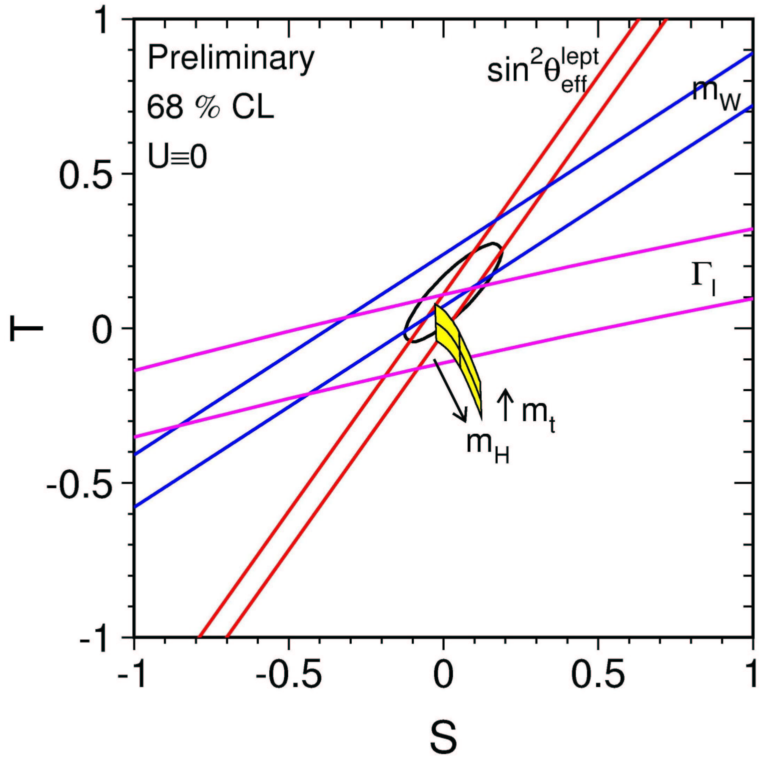


Limit on M_h goes from 219 GeV to M_h < 283 Gev

Best fit goes from 96 GeV to 126 GeV

SM works well

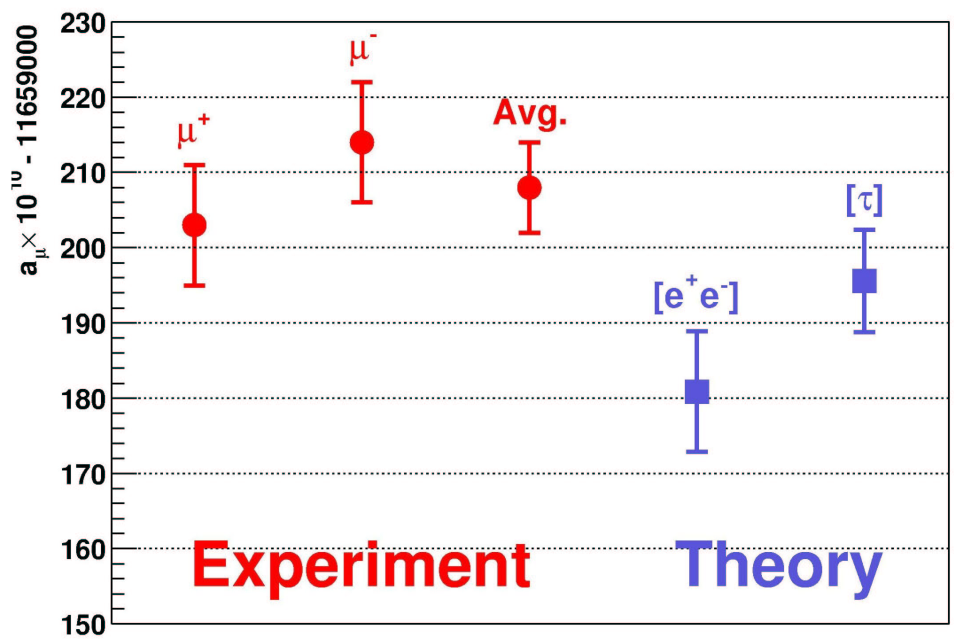
Fits to EW data



➢Fit assumes M_h=150 GeV

LEP EWWG 2003

New $(g-2)_\mu$ result

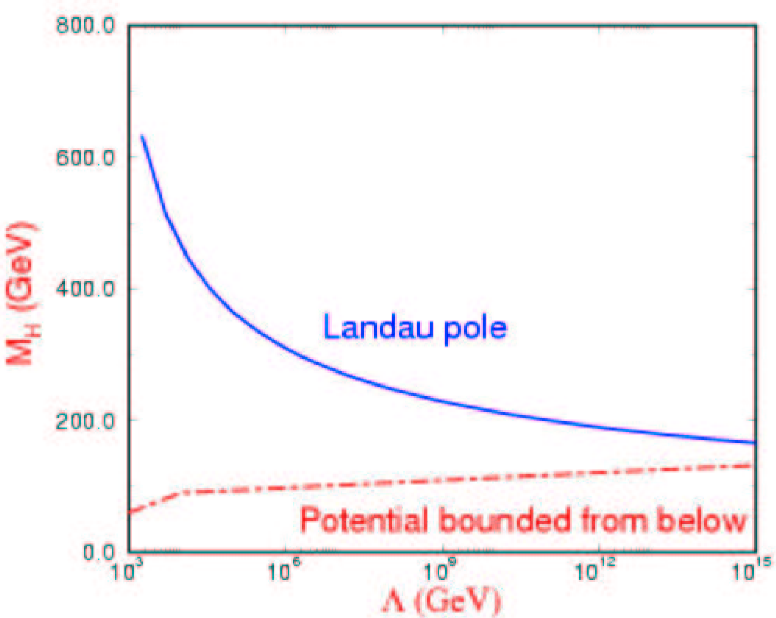


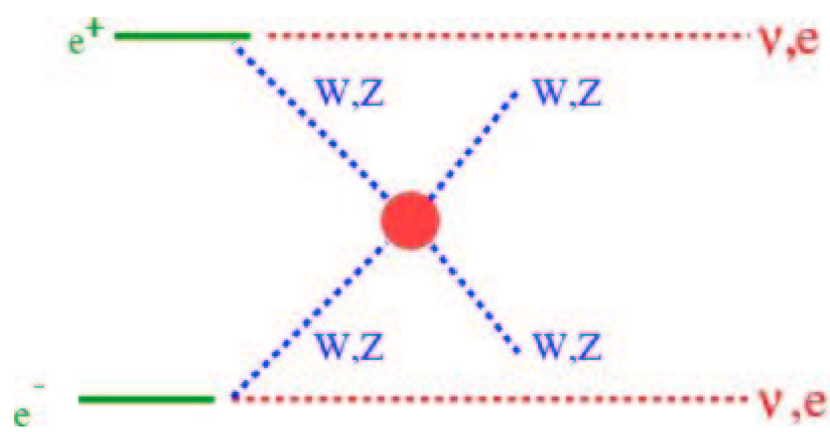
- ➢ e^+e^- data: 2.7σ effect
- ➢ τ data: 1.4σ effect

hep-ph/0401008

Where do we expect the Higgs?

➢ Allowed Higgs mass region related to "Scale of New Physics"

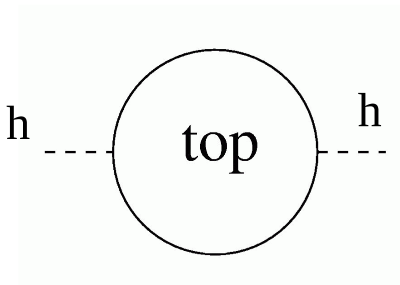


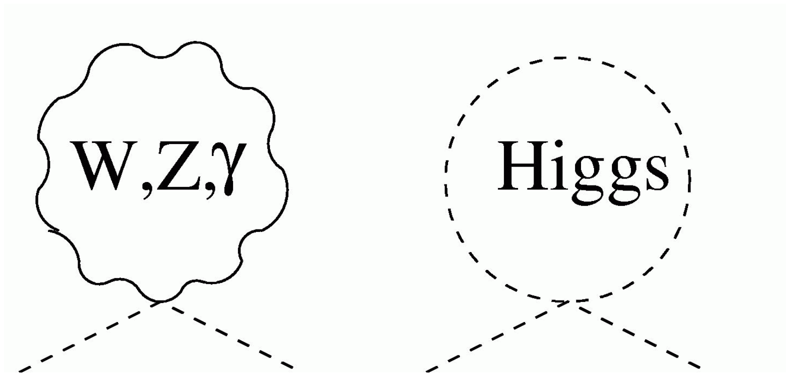


➢Standard Model inconsistent without Higgs unless new physics around 1.3 TeV

Light Scalars are unnatural

- Higgs mass grows with cut-off, Λ





$$\delta M_h^2 = \frac{G_F}{4\sqrt{2}\pi^2}\Lambda^2\left(6M_W^2 + 3M_Z^2 + M_h^2 - 12M_t^2\right)$$

$$= -\left(\frac{\Lambda}{0.7\ \mathrm{TeV}}\ 200\ \mathrm{GeV}\right)^2$$

$M_h \leq 200$ GeV requires large cancellations

The SM as an Effective Theory

- The SM is an effective low energy theory
  - Valid below some scale Λ
  - Assumes no new EW scale particles
- New physics effects parameterized in terms of higher dimension operators with SM fields
- 2 possibilities:
  - No Higgs $\Rightarrow$ Non-linear realization
  - Light Higgs$\Rightarrow$ Effective operators with Higgs bosons
- Assume CP, baryon #, lepton #, conservation

Assume light Higgs

- Effects of new physics appears as dimension 6 operators constructed with low energy fields

$$L_{eff} = L_{SM} + \sum \frac{f_i}{\Lambda^2} O_i + \ldots$$

- 12 CP conserving operators in Higgs/gauge sector
- Consider operators which affect W,Z 2-pt functions

$$O_{BW} = -\frac{gg'}{2} \varphi^+ B_{\mu\nu} W^{\mu\nu} \varphi$$

$$O_{\varphi,1} = (D_\mu \varphi)^+ \varphi^+ (D^\mu \varphi)$$

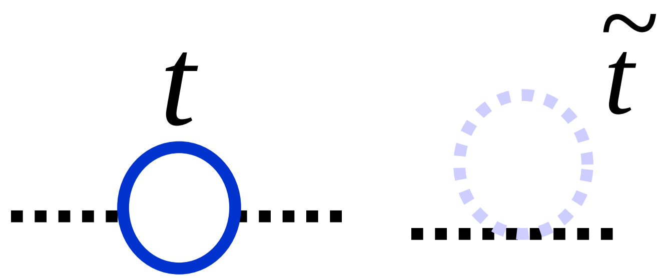
- LEP: $O_{\varphi,1} \Rightarrow \Lambda > 5$ TeV

Little Hierarchy: What explains why $\Lambda > 1$ TeV?

Giudice, hep-ph/0311344

SUSY….Our favorite model*

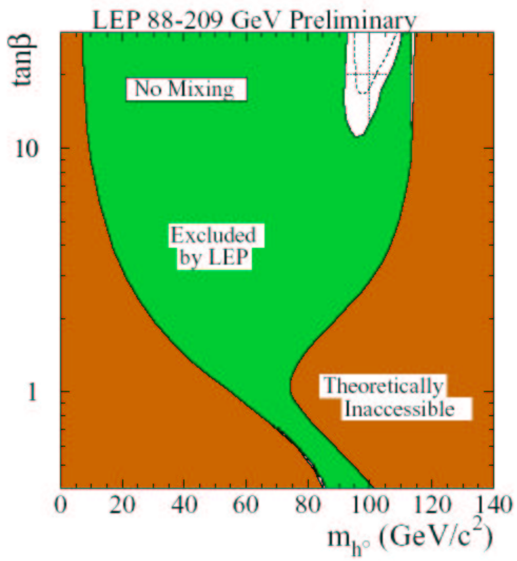
- Quadratic divergences cancelled automatically if SUSY particles at TeV scale
- Cancellation result of ***supersymmetry***, so happens at every order

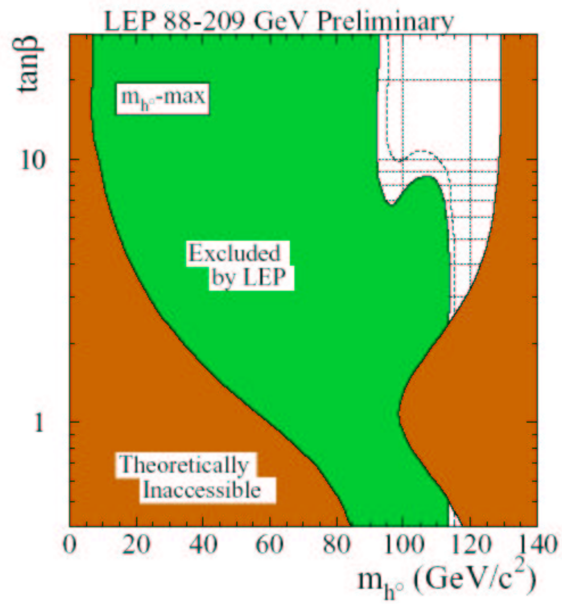


$$\delta M_h^{\,2} \approx (....) G_F \Lambda^2 (M_t^{\,2} - M_{\tilde{t}}^{\,2})$$

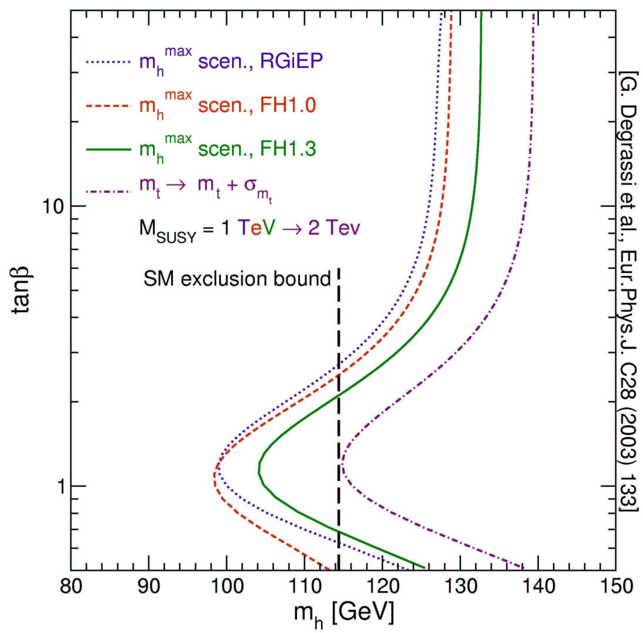
* Spires: 7421 papers after 1990 with title supersymmetry or supersymmetric!

LEP MSSM Higgs Bound





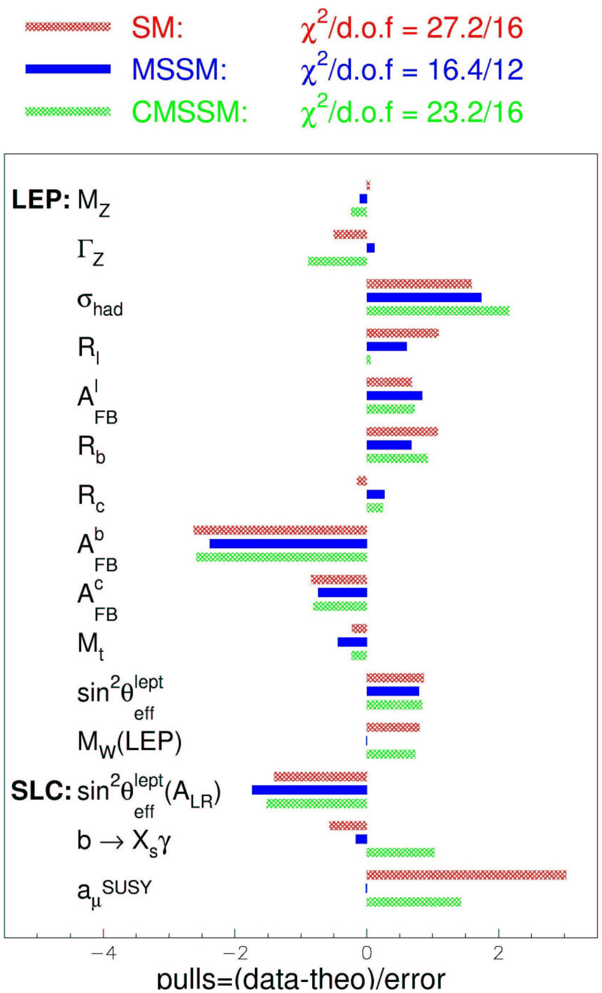
•Boundaries of theoretically inaccessible region ("the nose") have shifted due to 2- loop calculations of MSSM Higgs mass



With m_t=179 GeV, tan β exclusion disappears!

Precision measurements consistent with MSSM

- Fit precision data to MSSM

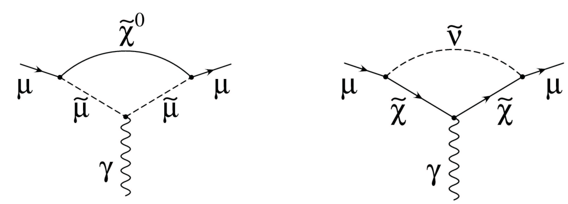


deBoer & Sanders, hep-ph/0307049

MSSM slightly better fit (17% prob) vs SM (5% prob)

MSSM prefers "light" SUSY

$(g\text{-}2)_\mu$ and $b \to s\,\gamma$ can be made to agree better with predictions by including light SUSY



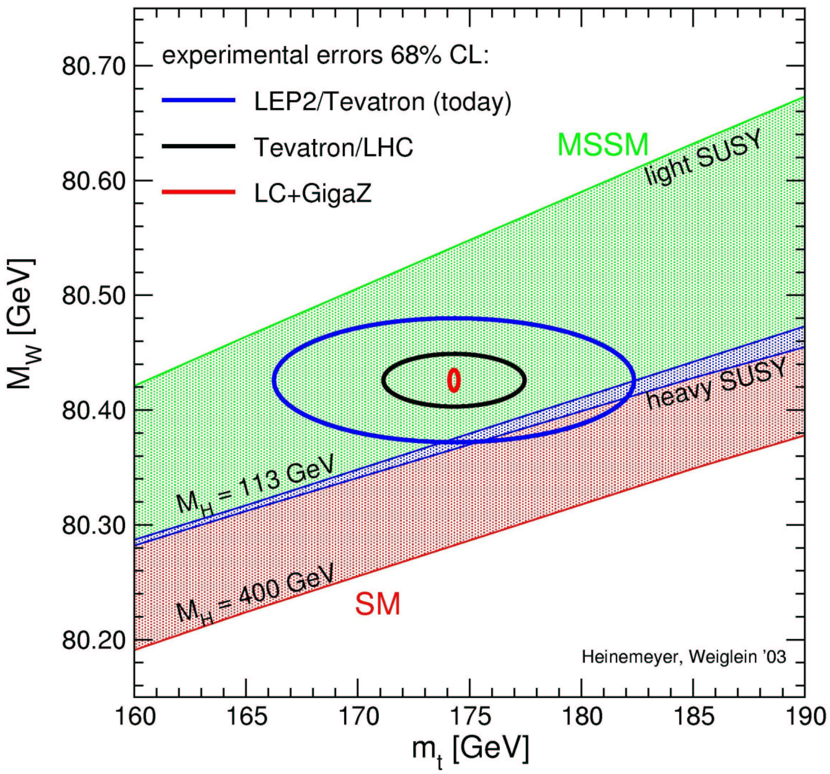
CMSSM: 5 parameters

m_0, $m_{1/2}$, A_0 $\tan\beta$, sign μ

➢Fit not as good as MSSM

Motivation for light SUSY….

- Improves SM fit
- Has Higgs boson just around the corner
- Large discovery potential at LHC/LC



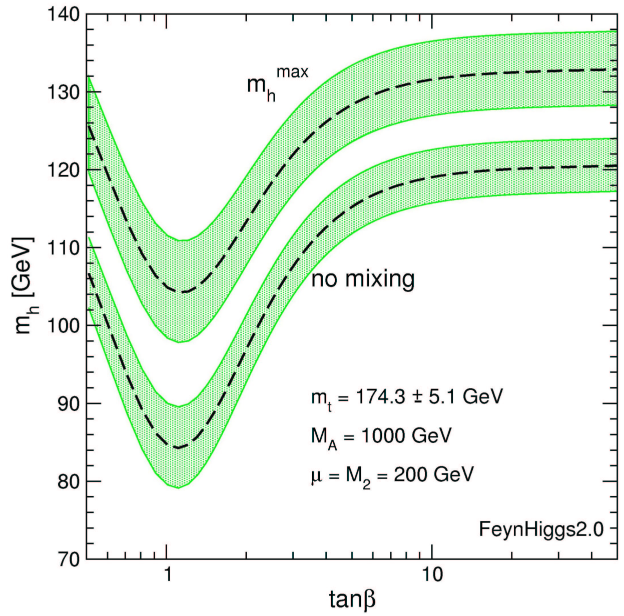
Heinemeyer & Weiglein, hep-ph/0307177

MSSM requires light Higgs

- Tension: stop should be **TeV scale** to cancel quadratic divergences in M_h from top loops
- Stop needs to be **heavy** so that lightest Higgs mass satisfies LEP bound,

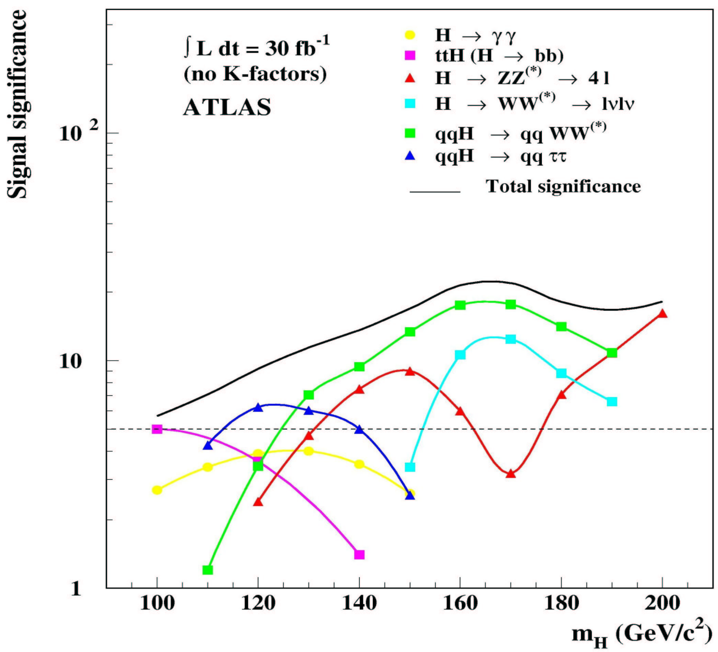
  $M_h > 114$ GeV

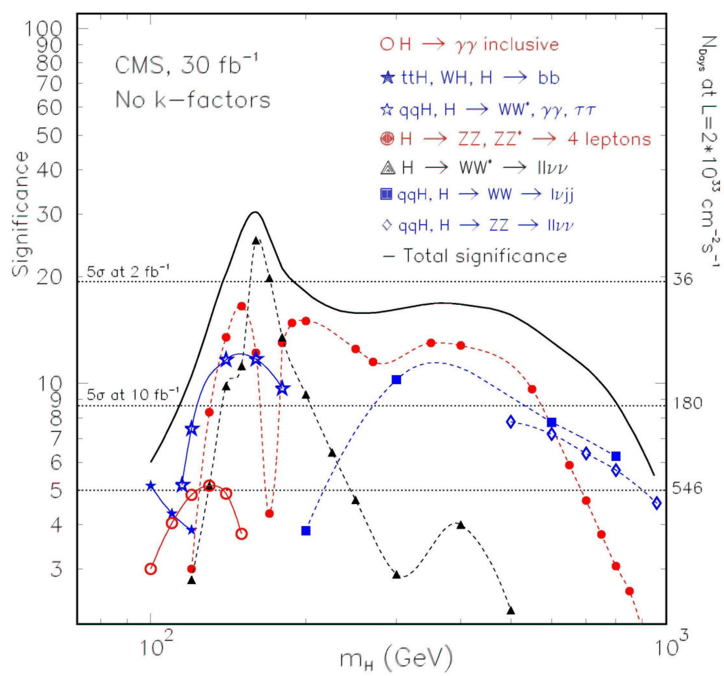
$$M_h^2 \le M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta} \ln\left[\frac{\tilde{m}_t^2}{m_t^2}\right] + \dots$$



Degrassi,Heinemeyer, Holliuk, Slavich, Weiglein, hep-ph/0212020

If there is a light SM Higgs, we'll find it at the LHC





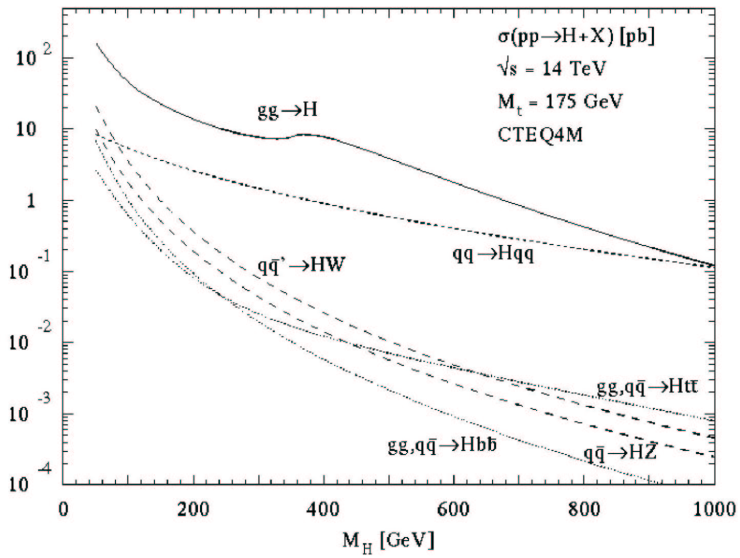
No holes in M_h coverage

Discovery happens early in the game!

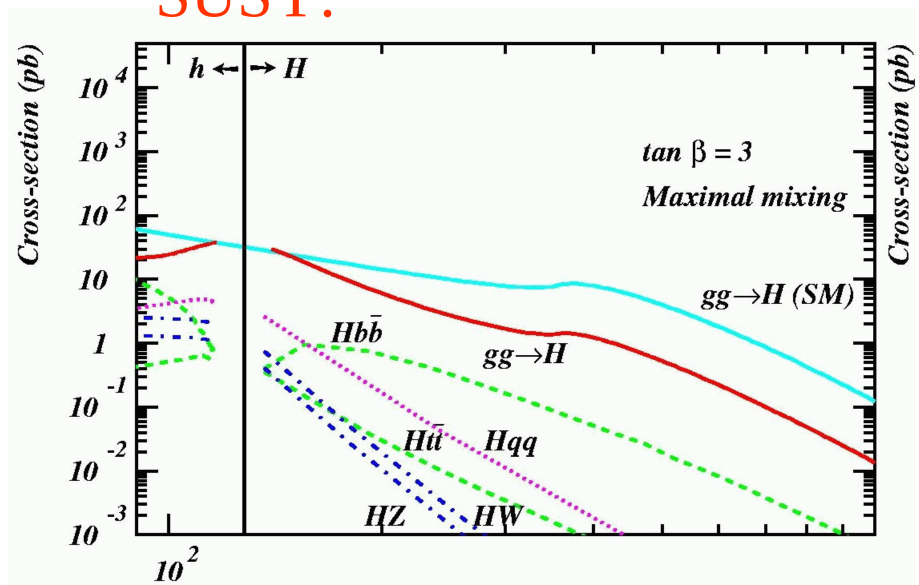
(plots are 30 fb^{-1})

Higgs at the LHC

SM:



SUSY:



- In SM $\sigma(bbh) \ll \sigma(gg \to h)$

- For small tan β, $\sigma(bbh)$ highly suppressed

For M_h<250 GeV, $\sigma(bbh) > \sigma(tth)$

b's add new wrinkle to Higgs production in SUSY

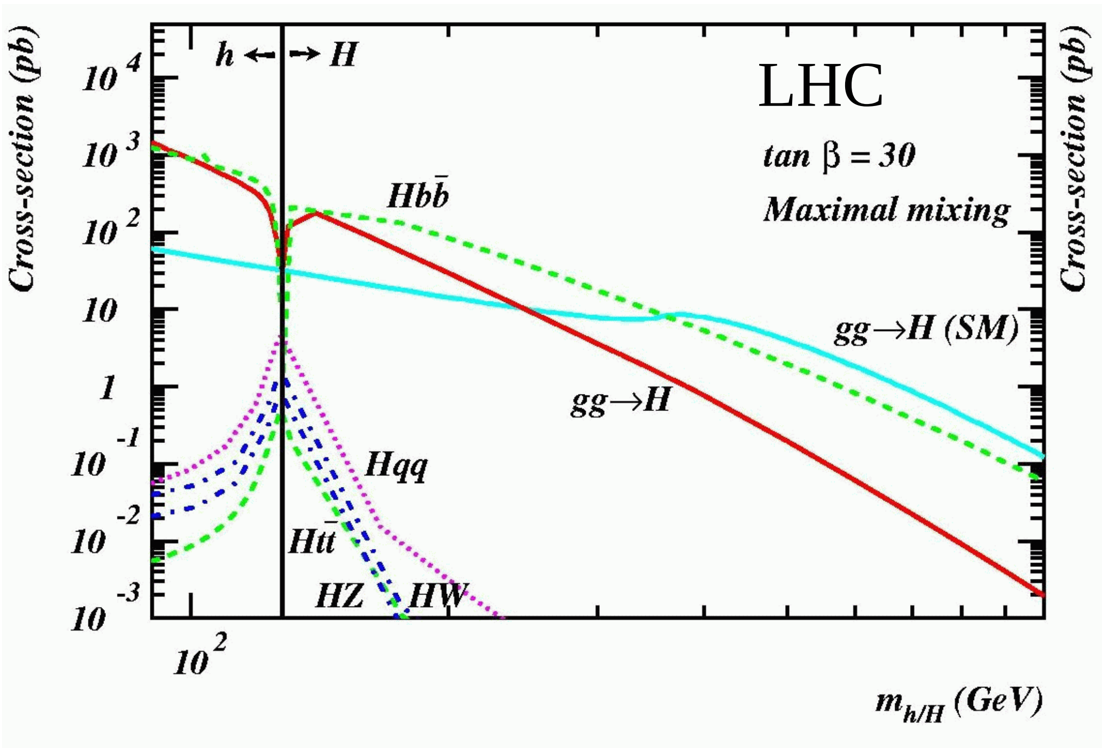
- Couplings of b to H/A enhanced at large tan β
- bb→H/A can dominate because:

$$\sigma_{bb} \approx \frac{m_b{}^2}{M_h{}^2} \tan^2 \beta$$

$$\sigma_{gg} \approx C_1 \cot^2 \beta + C_2 \frac{m_b{}^2}{M_h{}^2} + C_3 \frac{m_b{}^4}{M_h{}^4} \tan^4 \beta$$

Production of SUSY Higgs Bosons

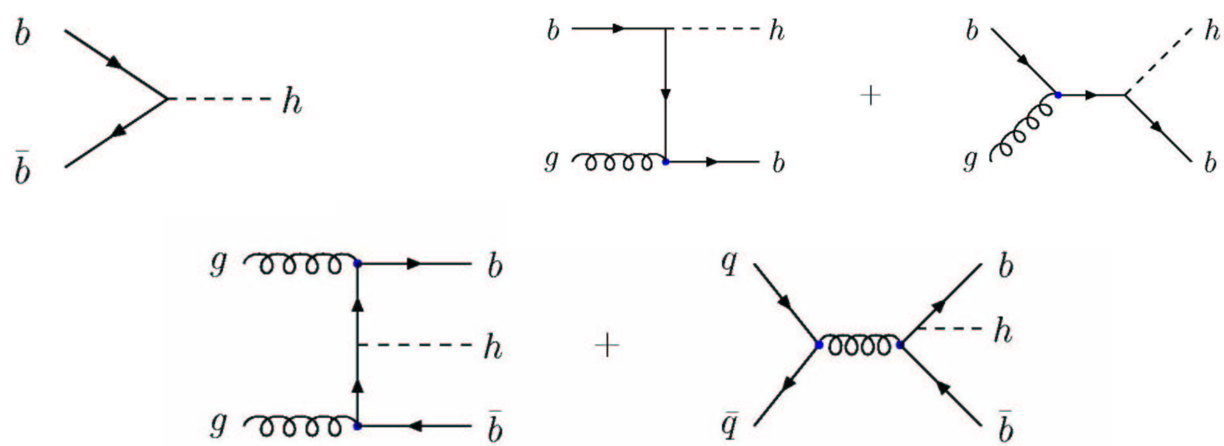
- For large tan β, dominant production mechanism is with b's
- bbh can be10x's SM Higgs rate in SUSY for large tan β



Spira

What is the dominant process?

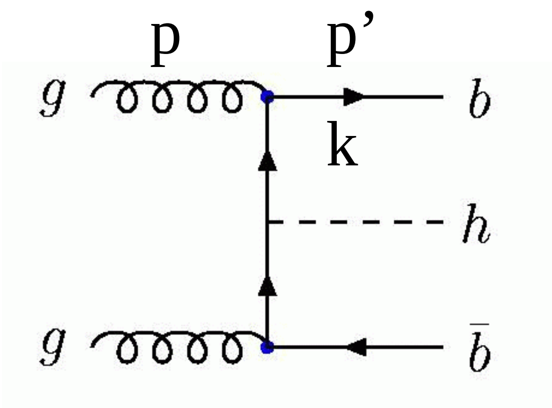
$$pp \to b\bar{b}h$$



Answer depends on whether you tag outgoing b's

Collinear Singularities

- g→bb splitting
  - Singular when b’s are collinear with initial gluon
  - m_b regulates singularity



Collinear limit:

p’=(1-z)p

k=zp

Internal propagator: $\dfrac{1}{(k^2 - m_b{}^2)} \rightarrow -\dfrac{1}{m_b{}^2}$

$$\left|A(gg \rightarrow bbh)\right|^2 \rightarrow (4\pi\alpha_s)\left|A(bg \rightarrow bh)\right|^2 \frac{P_{gb}(z)}{p \cdot p'}$$

The b quark as a parton

Phase space also factorizes in collinear limit:

$$(PS)_3 \to (PS)_2(\cdots)\int \frac{dE_b}{E_b}$$

- Integration over b phase space gives large log
- Absorb log into b quark distribution

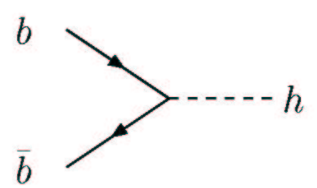
$$b(x,\mu) = \frac{\alpha_s}{2\pi}\ln\left(\frac{\mu^2}{Q^2}\right)\int_x^1 \frac{dz}{z}P_{bg}\left(\frac{x}{z}\right)g(z,\mu)$$

- Altarelli-Parisi evolution of PDFs sums $\alpha_s^n \ln^n(Q^2/m_b^2)$
  - Initial condition, $b(x,m_b)=0$
- b quark PDF $\approx \alpha_s \ln(Q^2/m_b^2)$ relative to gluon PDF
- Construct algorithm for including b's as initial state partons

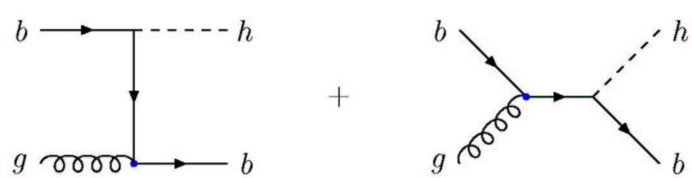
Aivazis, Collins, Olness, Tung

Consistent Counting for b initiated processes

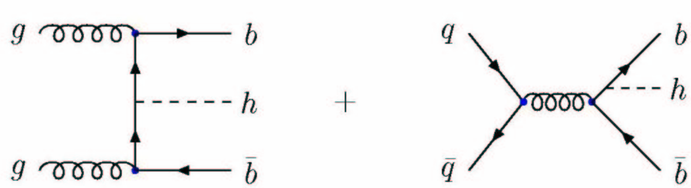
Large logarithms summed into b quark PDFs



$(\alpha_s \ln(M_h^2/m_b^2))^2$



$\alpha_s^2 \ln(M_h^2/m_b^2)$

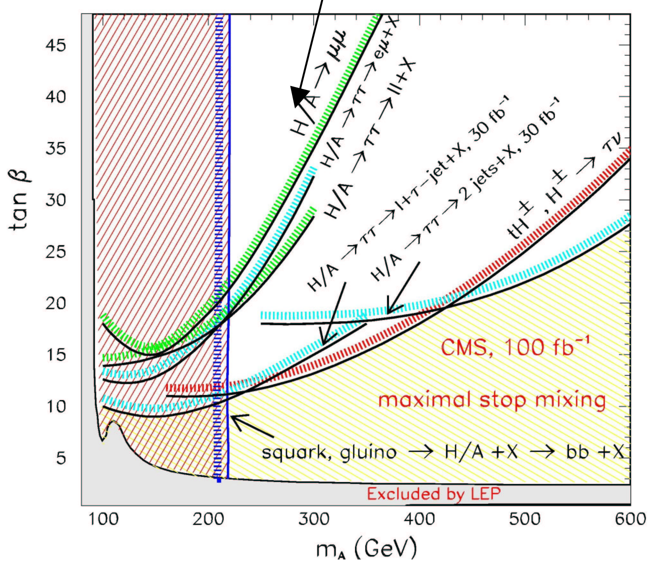


α_s^2

Dicus & Willenbrock, PRD39, 751 (1989)

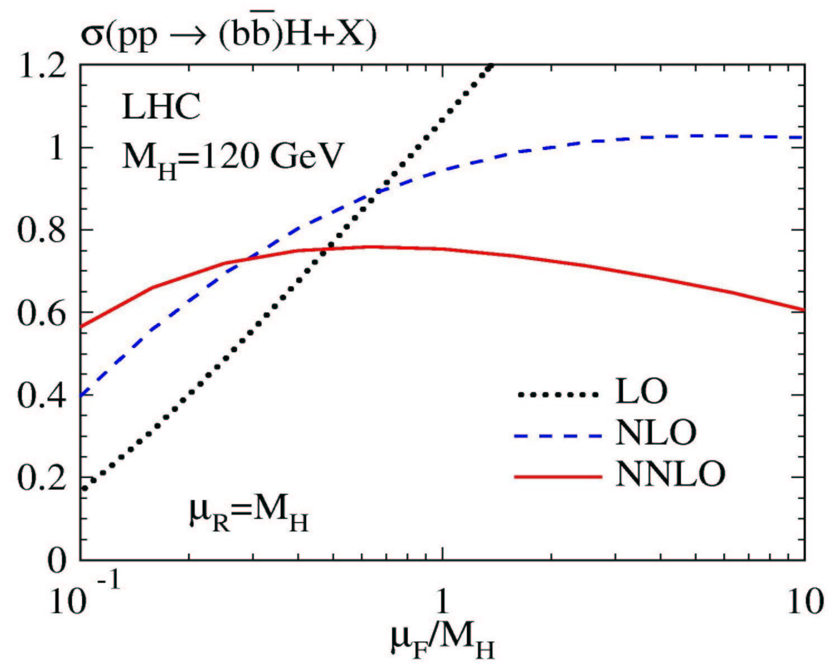
bb→h in MSSM

Single Higgs observable at large tan β through $H/A \to \mu^+\mu^-$, $\tau^+\tau^-$



➢Single Higgs rate computed from gg→h in CMS plot

Reduced theoretical error from reduced μ dependence



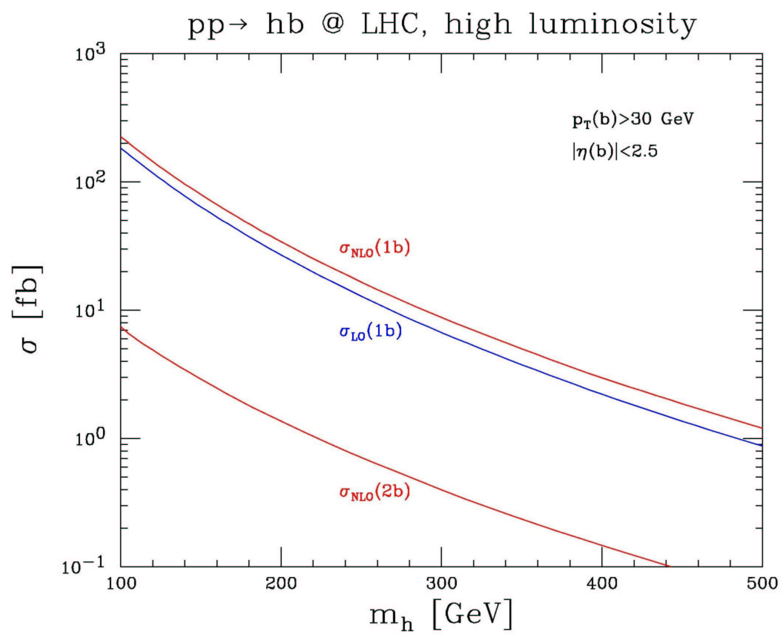
NLO: Maltoni, Sullivan, & Willenbrock, hep-ph/0301033

NNLO: Harlander & Kilgore, hep-ph/0304035

bh production at NLO

- More promising channel than bb→h
- Extra b tag and Higgs transverse momentum improve detection efficiency

SM at LHC:



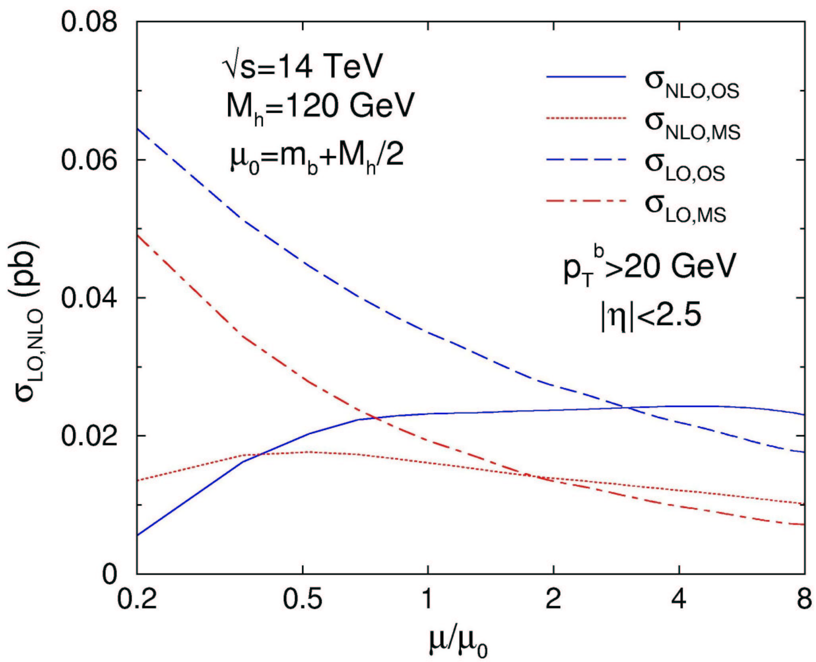
Campbell, Ellis, Maltoni, Willenbrock, hep-ph/0204093

gg→bbh at NLO

- Rate proportional to b quark Yukawa Coupling, m_b/v
- Lore: $\overline{MS}$ b mass sums logarithms

$$\overline{m}_b(\mu) = m_b\left(1 - \frac{\alpha_s(\mu)}{4\pi}\left[3\ln\left(\frac{\mu^2}{m_b^{\ 2}}\right) + 4\right]\right)$$

- Clearly true for $h \rightarrow bb$
- Many sources of logs in production process
- Large residual scheme dependence at NLO: formally $O(\alpha_s^4)$

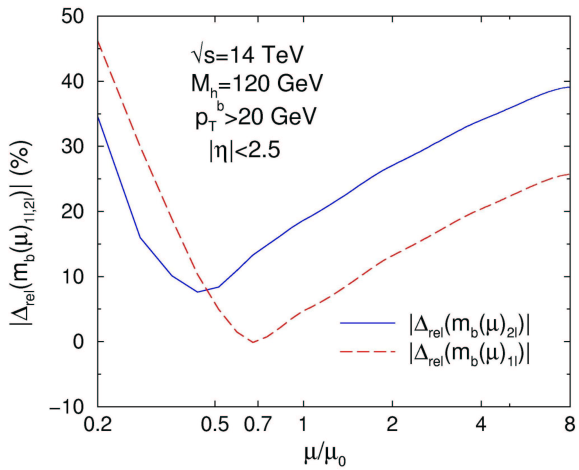


Dawson, Jackson, Reina, Wackeroth, hep-ph/0311067

Dittmaier, Kramer, Spira, hep-ph/0309204

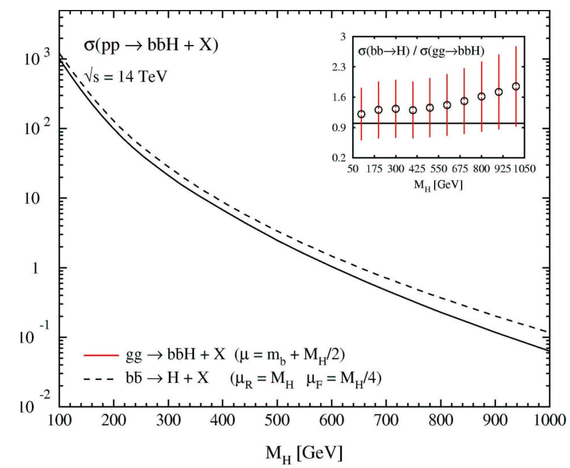
Theoretical Issues

- Large remaining scale/scheme dependence between OS and $\overline{MS}$ at NLO



- Effect ≈ 10-20%

$gg \rightarrow b\bar{b}h$ vs $b\bar{b} \rightarrow h$ at NLO



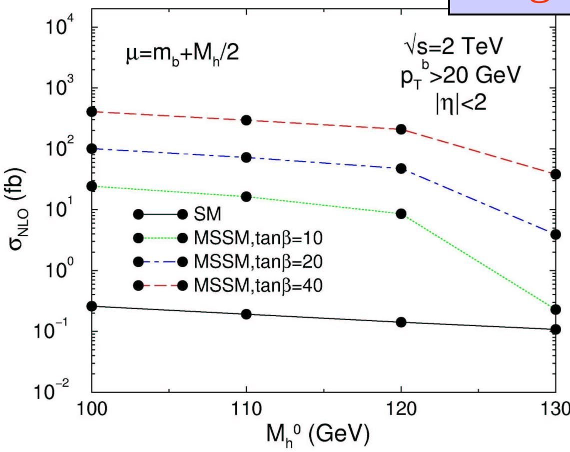
Note scale choice, $\mu=M_h/4$

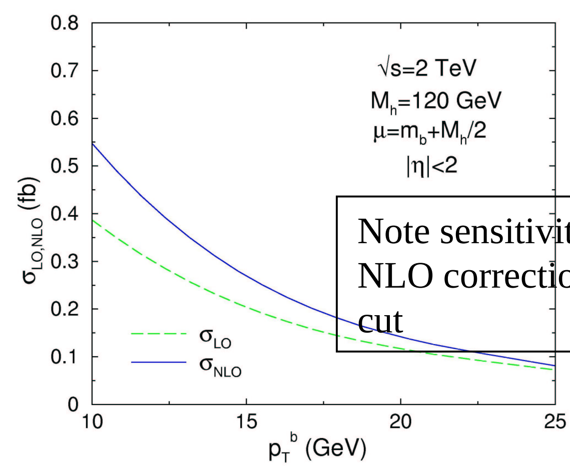
Dittmaier, Kramer, Spira, Les Houches03

Maltoni, Sullivan, Willenbrock, hep-ph/0301033

bbh in SUSY Models at Tevatron

Huge enhancements in SUSY

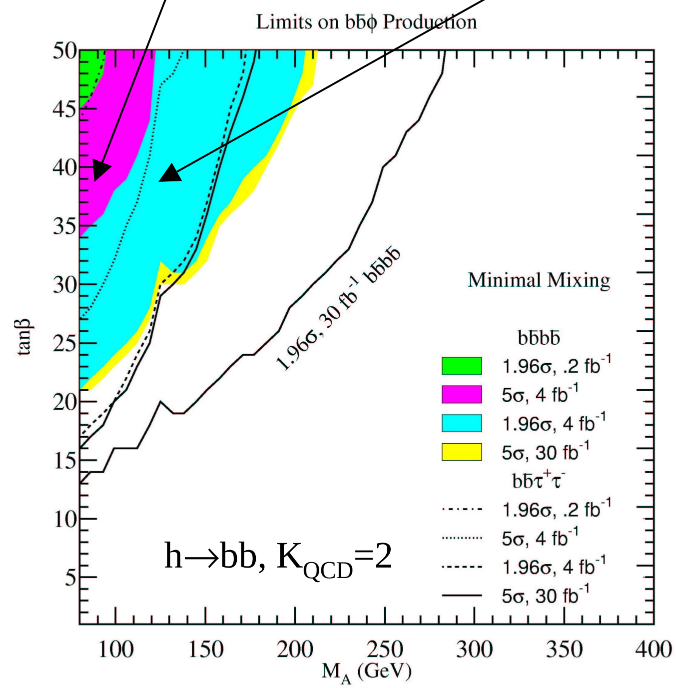




Note sensitivity of NLO corrections to p_T cut

5σ discovery with 4 fb^{-1}

95% exclusion with 4 fb^{-1}

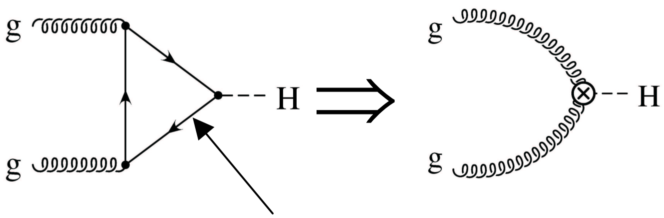


Dawson, Jackson, Reina, Wackeroth, hep-ph/0311067

Carena, Mrenna, Wagner, hep-ph/9808312

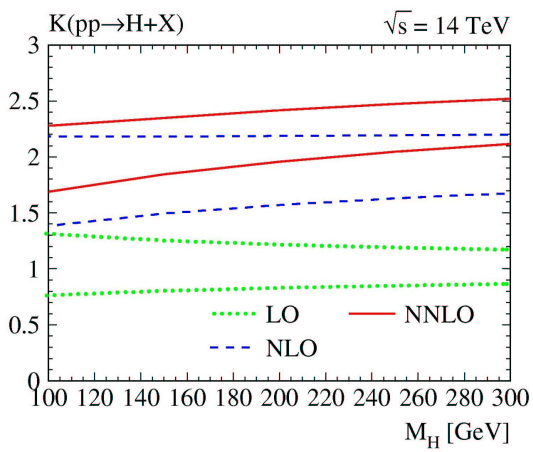
Dittmaier, Kramer, Spira, hep-ph/0309204

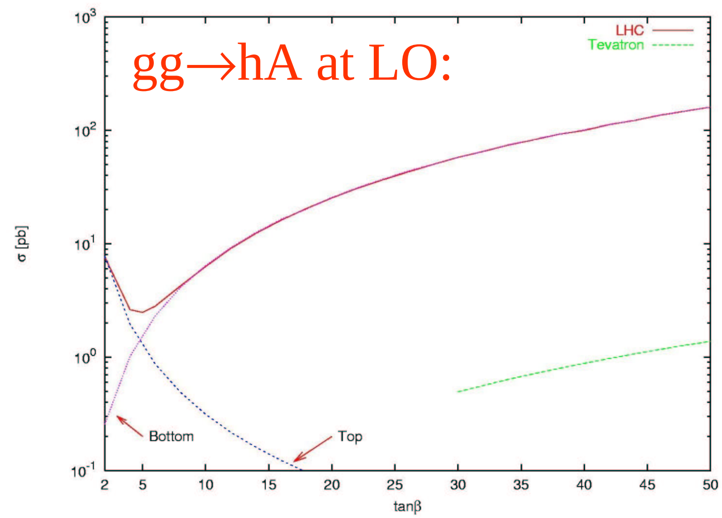
NNLO corrections done in large m_t effective theory



Only top in loop

- Effective theory not valid when b contributions important





- tan β > 5, b loops dominate

Harlander & Kilgore, hep-ph/0201206,

Anastasiou, Melnikov, hep

Field, Dawson, Smith, hep-ph/0311199

One Argument for MSSM is Grand Unification

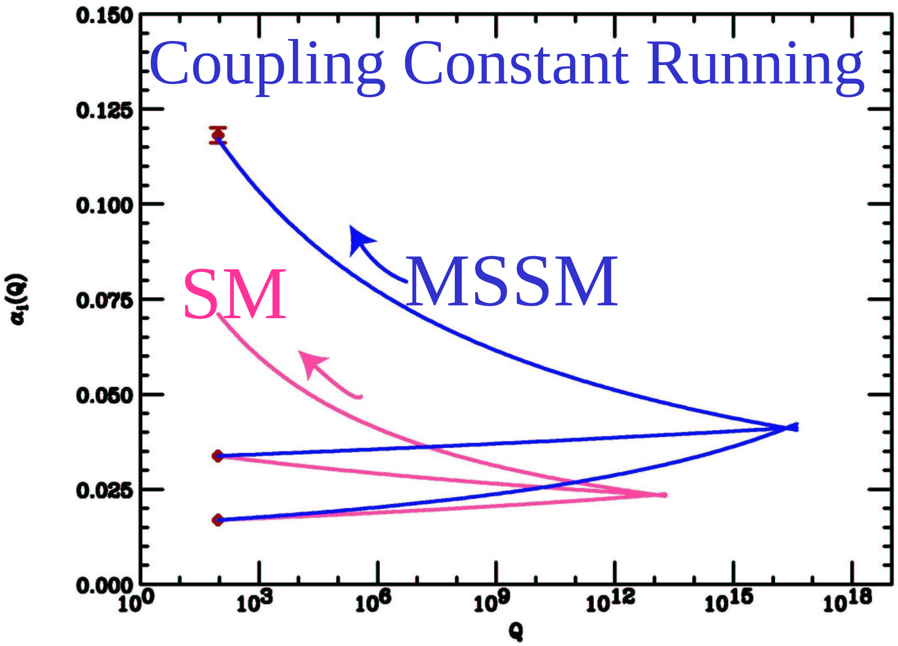
- 1 loop RGE, SU(5) normalization of U(1):

$$B = \frac{1/\alpha_3 - 1/\alpha_2}{1/\alpha_2 - 1/\alpha_1} = .53(SM),\ \ .71(MSSM)$$

- Experimentally, B=.717± .008
- 2 loop RGE, TeV scale threshold effects weaken argument:

  MSSM: $\alpha_s(M_Z) > .13$

  PDG: $\alpha_s(M_Z) = .1171 \pm .0014$
- Restoring agreement requires large GUT scale corrections



Peskin, hep-ph/0212204

Bagger, Matchev, Pierce, Zhang

Gauge Singlets don't spoil Unification

- Simplest modification of MSSM: add Higgs singlet S
- Superpotential, $W = \lambda_1 H_u H_d S + \frac{\kappa}{3} S^3$
  - S^3 term necessary to avoid PQ Axion
  - $\lambda \langle S \rangle H_u H_d$ naturally generates $\mu H_u H_d$ term
- At tree level, lightest Higgs mass bound becomes,

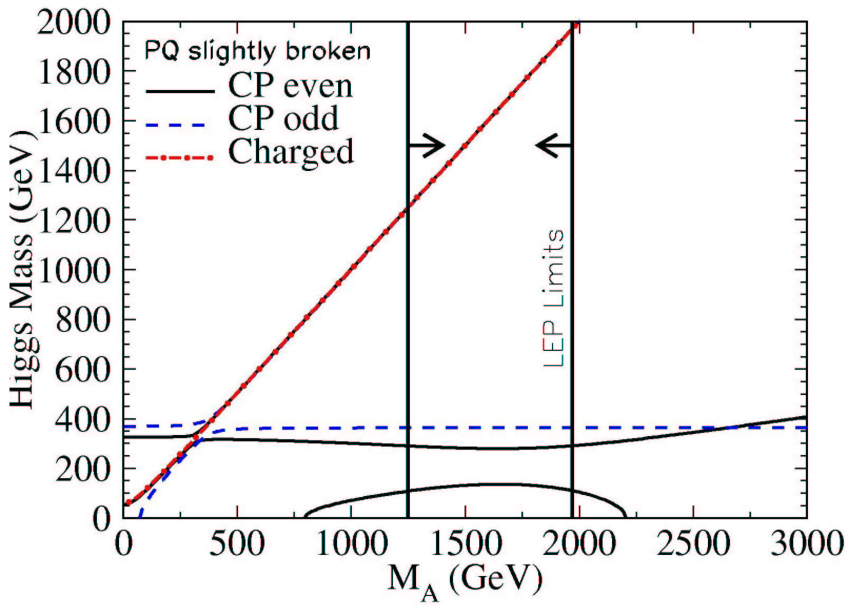
$$\boxed{M_h^{\ 2} \leq M_Z^{\ 2} \cos^2 2\beta + v^2 \lambda_1^{\ 2} \sin^2 2\beta}$$

- Assume couplings perturbative to M_{GUT} and SUSY scale ≈1 TeV
  - $M_h < 150$ GeV with singlet Higgs
- Singlets can be consistent with precision measurements
- Phenomenology very different from MSSM
  - 3 neutral Higgs boson, 2 pseudoscalars, 1 charged Higgs
  - Many scenarios have h, A at weak scale

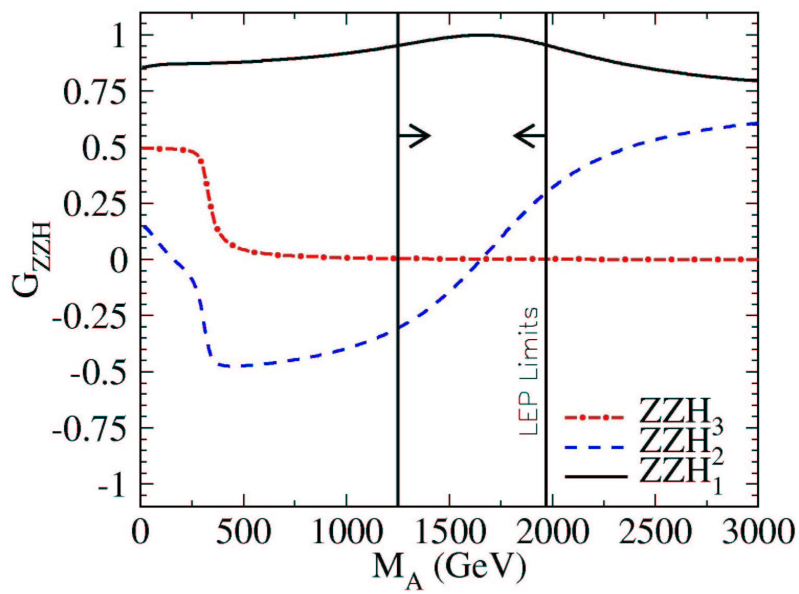
Espinosa & Quiros, hep-ph/9809269,Kobe & Wells, 2002

NMSSM Higgs Mass Spectrum

Typical Scenario:



ZHH couplings suppressed



- Heavy, roughly degenerate H_3, A_2, $H^{\pm}$

- Spectrum of light Higgs: 2 light scalars, 1 light pseudoscalar

Very different from MSSM!

New Decays:

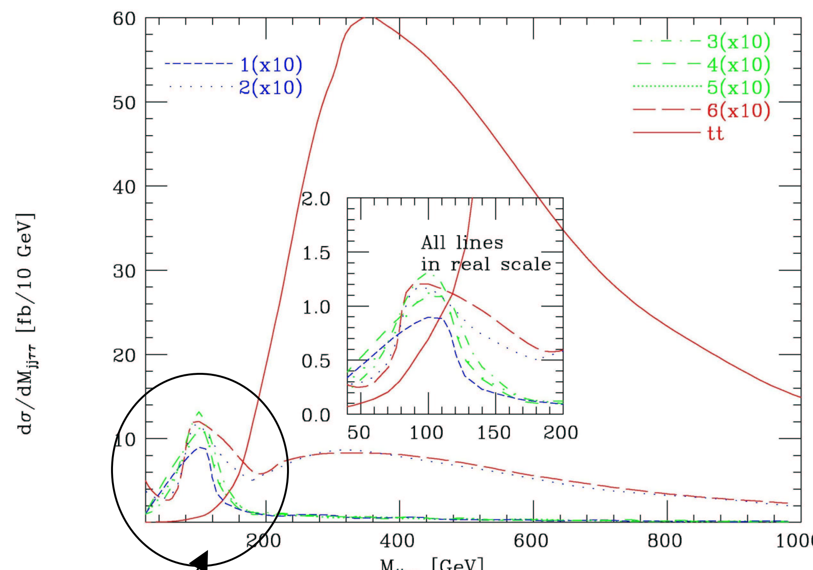
$A_1 \rightarrow H_1 H_1$, $H_2 \rightarrow A_1 A_1$

Miller, Nevzorov, Zerwas, hep-ph/0304049

MSSM, h→AA excluded Experimentally

- h→AA important discovery channel in NMSSM
- h can be SM-like and A light in NMSSM
- Look for
  - $W^+W^- \to h \to AA \to \tau^+\tau^- jj$
  - Dominant background from tt
  - Statistically significant at LHC with 300 fb^{-1}/detector

Curves are different models



•Look for enhancement at low mass

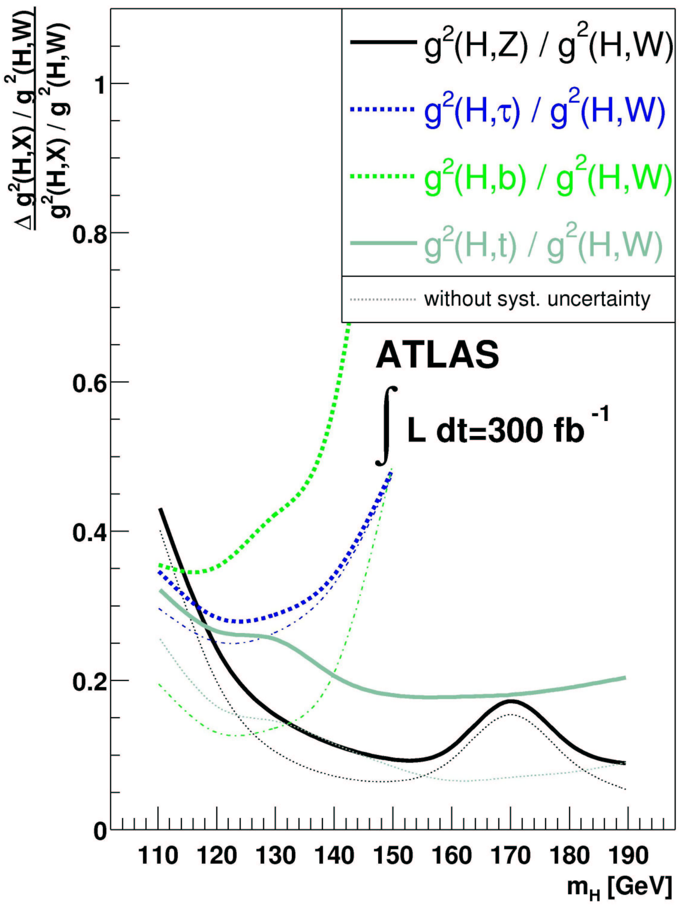
•Not Gold-Plated!

Ellwanger, Gunion, Hugonie, Moretti, hep-ph/0305109

If we find a “Higgs-like” object, what then?

- We need to:
  - Measure Higgs couplings to fermions & gauge bosons
  - Measure Higgs spin/parity
  - Reconstruct Higgs potential
- Reminder: Many models have other signatures:
  - New gauge bosons (little Higgs)
  - Other new resonances (Extra D)
  - Scalar triplets (little Higgs, NMSSM)
  - Colored scalars (MSSM)
  - etc

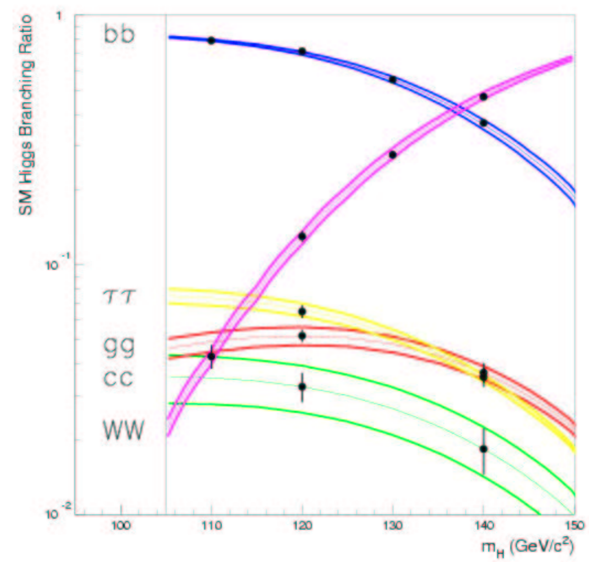
Absolute measurements of Higgs couplings



Duhrssen, ATL-PHYS-2003-030

e^+e^- LC at $\sqrt{s}$=350 GeV

L=500 fb^{-1}, M_H=120 GeV



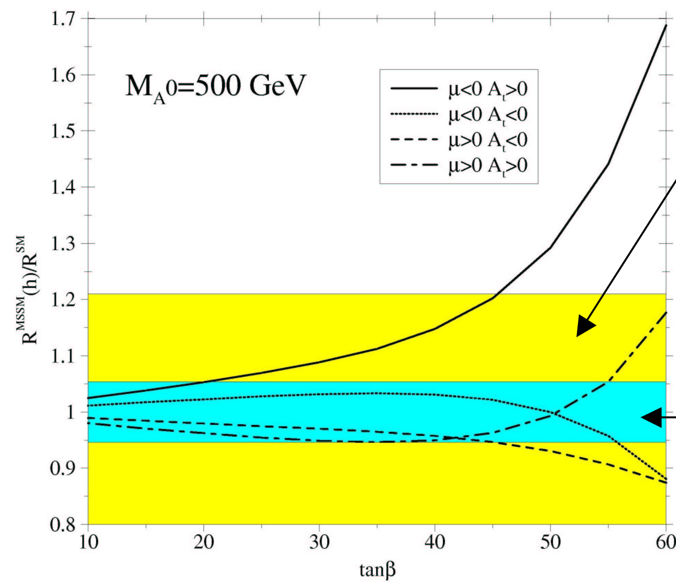
Battaglia, Desch, hep-ph/0101165

LC can measure g_{ZZh} to 1-2% through $\sigma(e^+e^- \rightarrow Zh)$

How well do we need Higgs couplings?

- MSSM example:

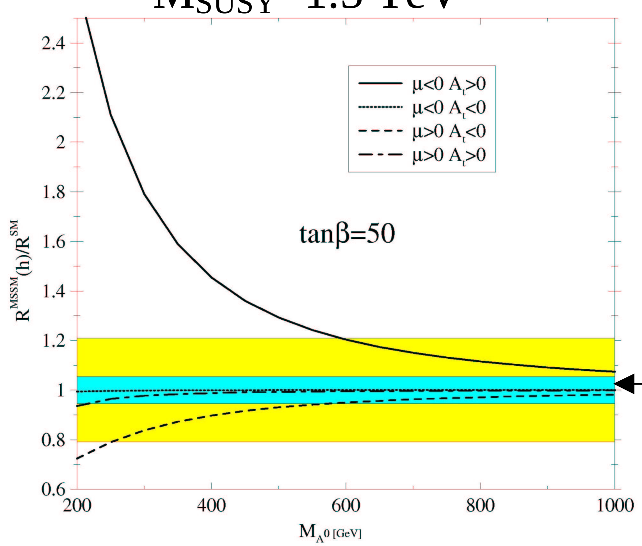
$$R = \frac{BR(h \to b\bar{b})}{BR(h \to \tau^+ \tau^-)}$$



21% deviation from SM

5.4% deviation from SM

M_{SUSY}=1.5 TeV



Note rapid approach to decoupling limit

Guasch, Hollik, Penaranda, hep-ph/0307012

Conclusions

- SM works well with light Higgs
  - Scale for extensions pushed by precision measurements
- Role of b quark in Higgs production calculations in MSSM presents new theoretical challenges
  - New production mechanisms
  - Need for NNLO without large m_t effective theory
- We need to think outside the MSSM box
  - New effects in NMSSM
  - Precision measurements of Higgs couplings can distinguish between models